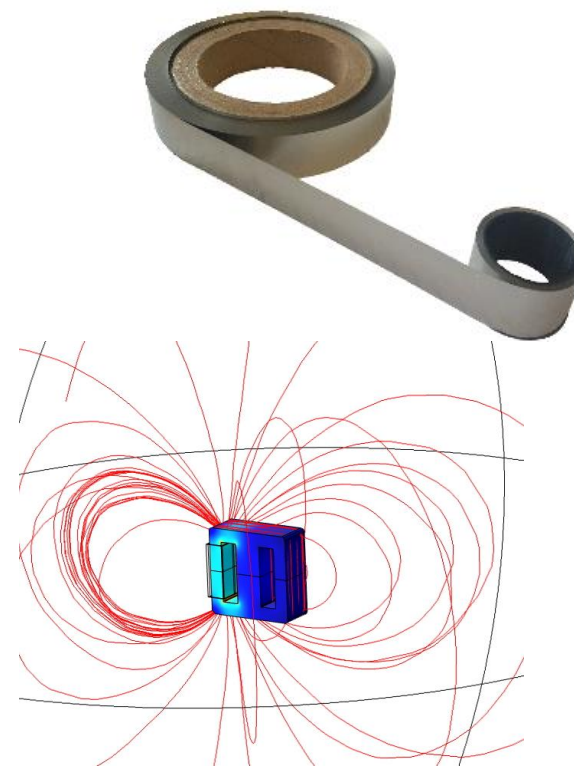
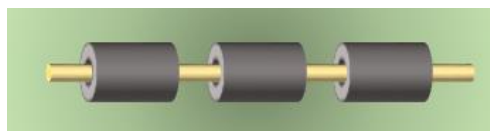
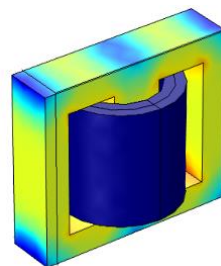


# Research in Soft Magnetic Materials at NASA Glenn

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Randy Bowman



*NASA Glenn Research Center*

August 10<sup>th</sup>, 2017

# Establishment of Magnetism Research Activities

*Magnetic materials have not historically been an active research topic at NASA GRC*

## Motivation for Entering the Field:

Center-Level Motivation – Develop GRC expertise and capabilities in magnetic materials and initiate a presence in the application and research communities to support the future direction of NASA GRC, which emphasizes more vehicle electrification and “green” power generation and power conversion technologies.

Specific Tasks - Support the needs of the **Advanced Air Transport Technology** (AATT) Project by developing more capable soft and hard magnetic materials for use in motors, power conversion, and control circuitry for the Hybrid electric program.

## Support and Main Activities:

- Thus far, the AATT project has provided the majority of the funding needed to establish the magnetism program at GRC.
- Program has been highly focused thus far on scale-up, manufacturability and component fabrication to support hybrid electric concepts.
- Also pursuing fundamental research on material behavior and alloy development.
- Funding has been augmented by other internal and external programs.
- Producing hardware and testing for external programs.
- Establishing a commercialization path with industry for these materials.

# Establishment of Magnetism Research Activities

*The timing of NASA's interest in magnetism was fortuitous. NETL and CMU groups were looking for a location to host the large melt spin casters.*

## Equipment

3-kg caster – Returning this unit to operational status was key to producing large-scale components. This is necessary for determining the behavior of developmental alloys under relevant operating conditions.

## Partnerships

Gave NASA access to the corporate knowledge that the NETL/CMU teams had accumulated and allowed us to contribute quickly.

# Rationale for Material Investment

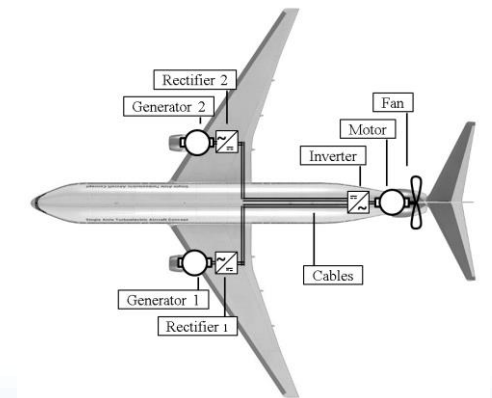
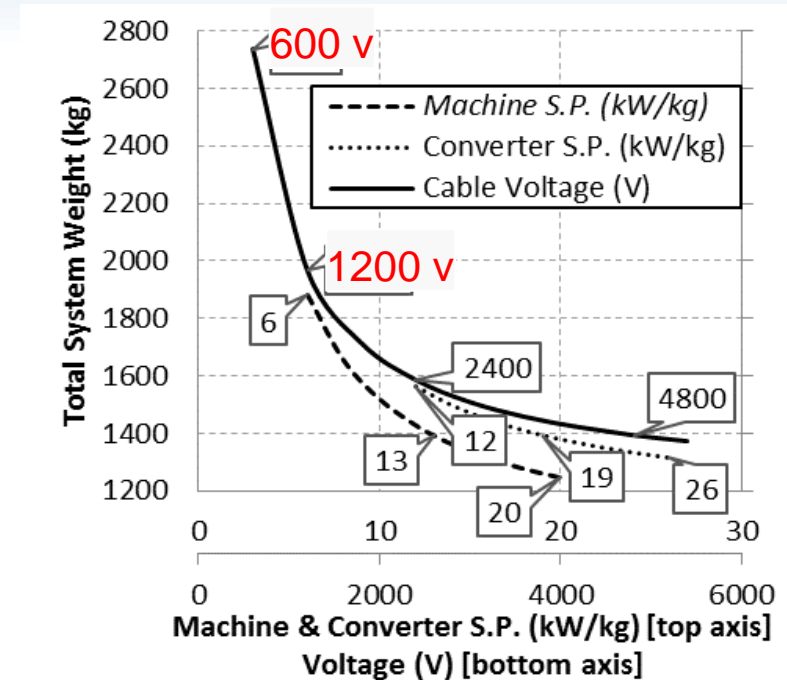
## ...Weight, Weight, Weight

Power system weights are very sensitive to

- Electrical Efficiency
- Component Specific Power
- Distribution Voltage

### Key Material Technologies

- Wide band gap semiconductors—increasing frequency increases efficiency
- Magnetic Materials—increasing frequency and reducing component losses
- Insulation Materials—enabling higher distribution voltage
- Advanced Conductors—high risk / high payoff investment in new systems



Ref: Jansen et al., AIAA, 2016

# Enabling Materials for Electrified Propulsion

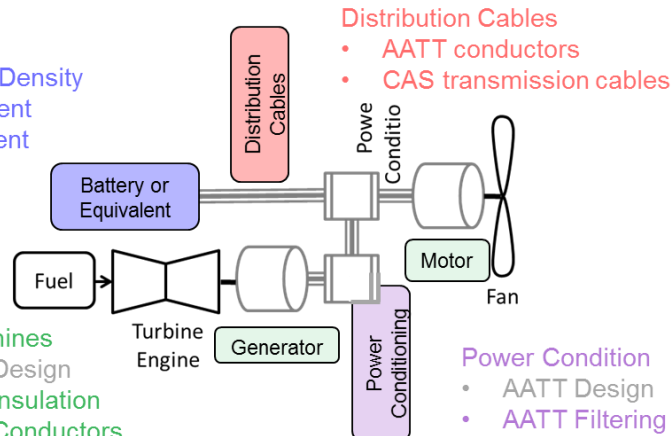
## Power System Weight Drivers

### Improved Power Density

- OGA investment
- CAS investment

### Elec. Machines

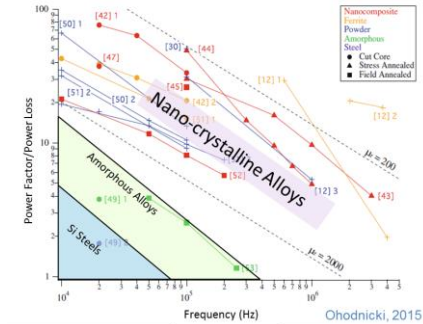
- AATT Design
- AATT Insulation
- AATT Conductors
- CAS Manufacturing



## Magnetic Materials

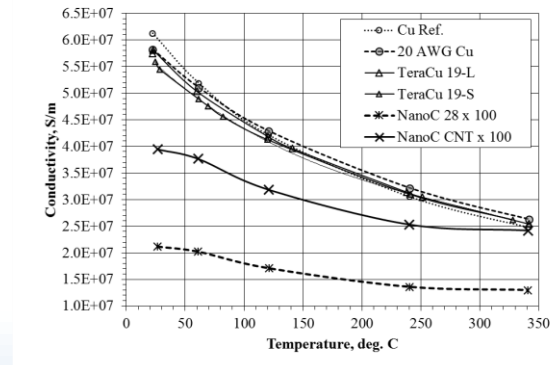
### High Efficiency Component Development

- Inductor Filters – for 20 kHz ripple suppression in motor controllers
- DOE sponsored PV-to-grid integration transformer



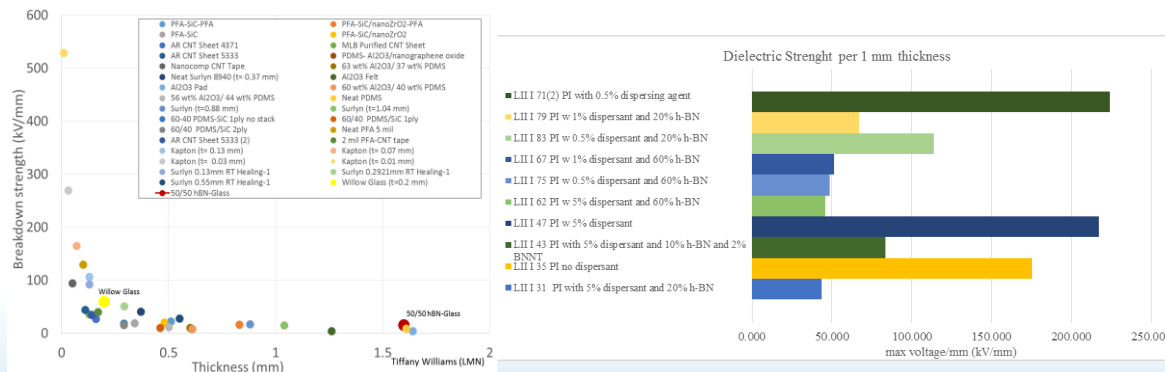
## High Conductivity Materials

- Theoretically CNT or graphene has high conductivity
- Limited evidence of specific conductivity improvements
- Looking at separated “metallic” CNT

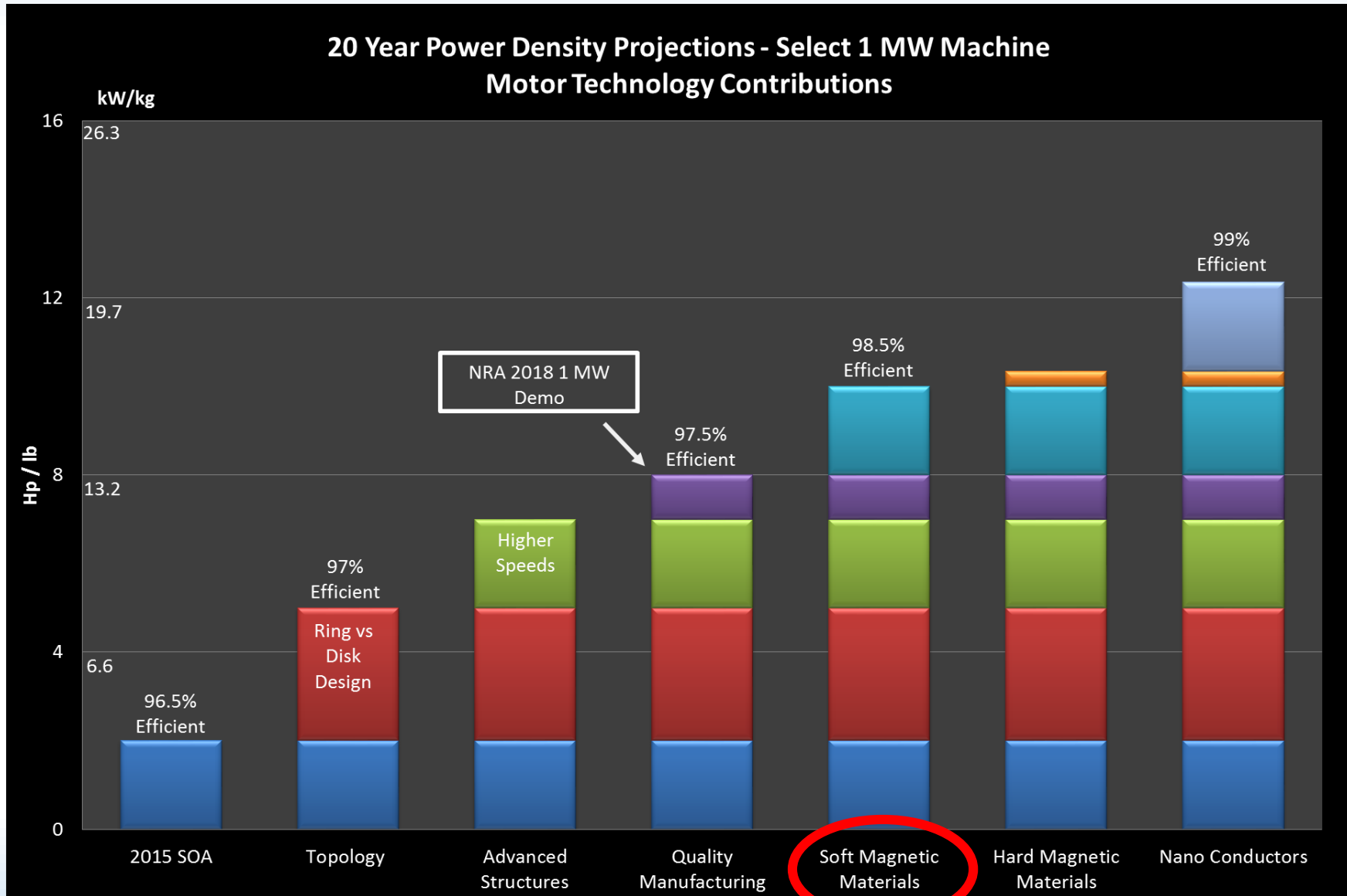


## Insulation Materials

- Survey organic/inorganic composite solutions
- Quantify thermal bottlenecks
- Enable novel materials/engineering solutions



# Technology Impact on Specific Power



Soft magnetic materials are considered to be a key technology for closing the hybrid electric design space.

**Objective:** Develop soft magnetic materials that possess low losses at high switching frequencies

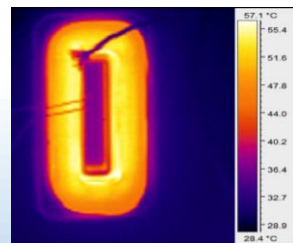
Energy conversion/transformation requires the use of soft magnetic materials. Important for motors, filters, transformers, etc.

Faraday's Law of induction:

$$\begin{aligned} \text{electromotive force} &\rightarrow \epsilon = -\frac{d\Phi}{dt} \leftarrow \text{time-changing Magnetic flux} \\ \text{flux density (induction)} &\rightarrow \Phi = \mathbf{B} \cdot \mathbf{A} \leftarrow \text{area} \\ \mathbf{B} &= \mu_0(\mathbf{H} + \mathbf{M}) \\ &\quad \uparrow \quad \quad \uparrow \quad \quad \uparrow \\ &\quad \text{permeability of free space} \quad \text{magnetic field} \quad \text{magnetization} \end{aligned}$$

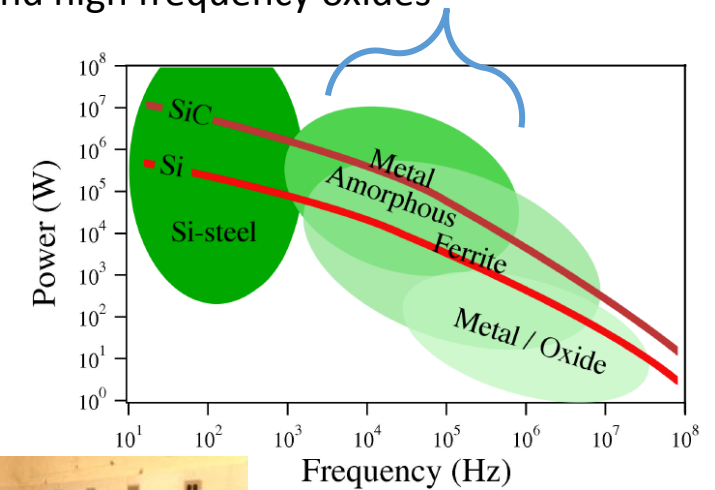
**Most devices/components benefit from higher operating frequencies, which results in higher power densities (higher output and lower volume)**

But electrical losses (resulting in internal heat generation) also increase with frequency.

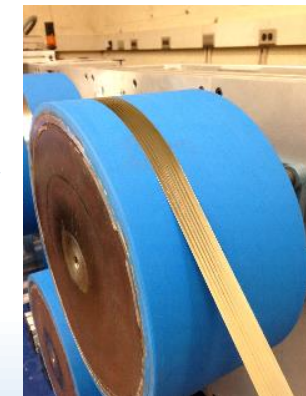


**Approach:** Develop and produce nanocomposite materials fabricated via rapid solidification casting, followed by post-processing, to produce **tailored** magnetic properties

These amorphous and nanocrystalline materials bridge the large gap between low frequency steels and high frequency oxides



Cast ribbon



Strain annealing

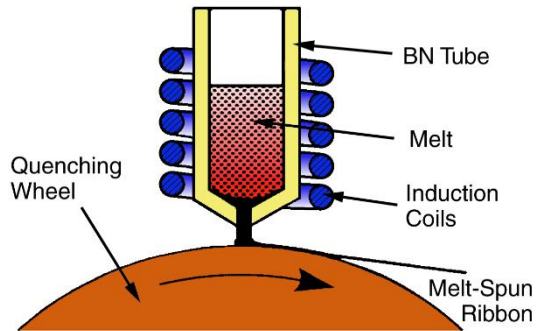


Coated transformer core

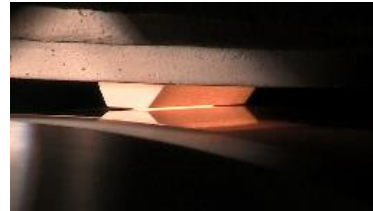


# Amorphous Ribbon Production

Production-scale and research-grade rapid solidification casters



Molten metal ejected from nozzle onto rotating wheel



Rapid solidification produces low-loss magnetic materials due to nano-size microstructural features

Casting produces 20-micron thick, 25 mm-wide ribbon



Small caster is useful for alloy development and for alloys that require protective environments

Research Caster. Inert atmosphere.



Large (5-kg) Rapid Solidification Caster



Largest US-owned rapid solidification caster

*The ability to cast large quantities of wide ribbons gives GRC unique capability in the field.*



# Amorphous and Nanocomposite Ribbons Produced at GRC

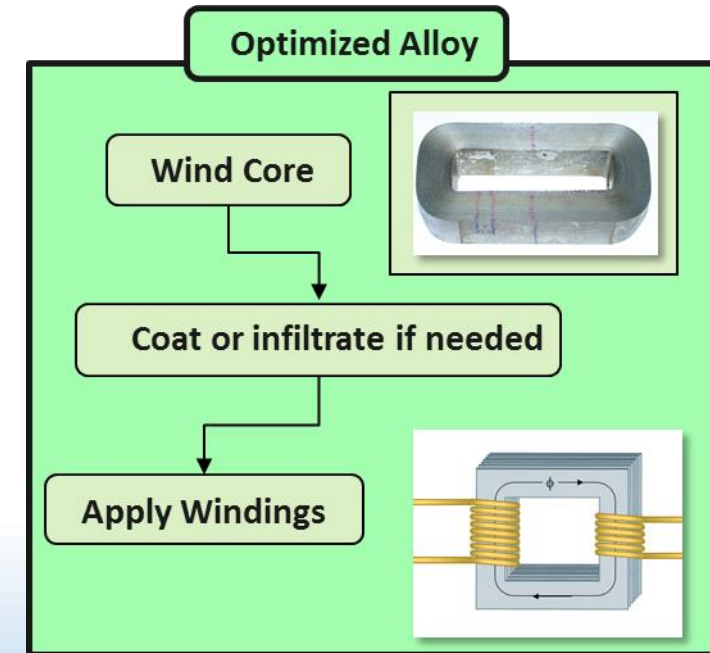
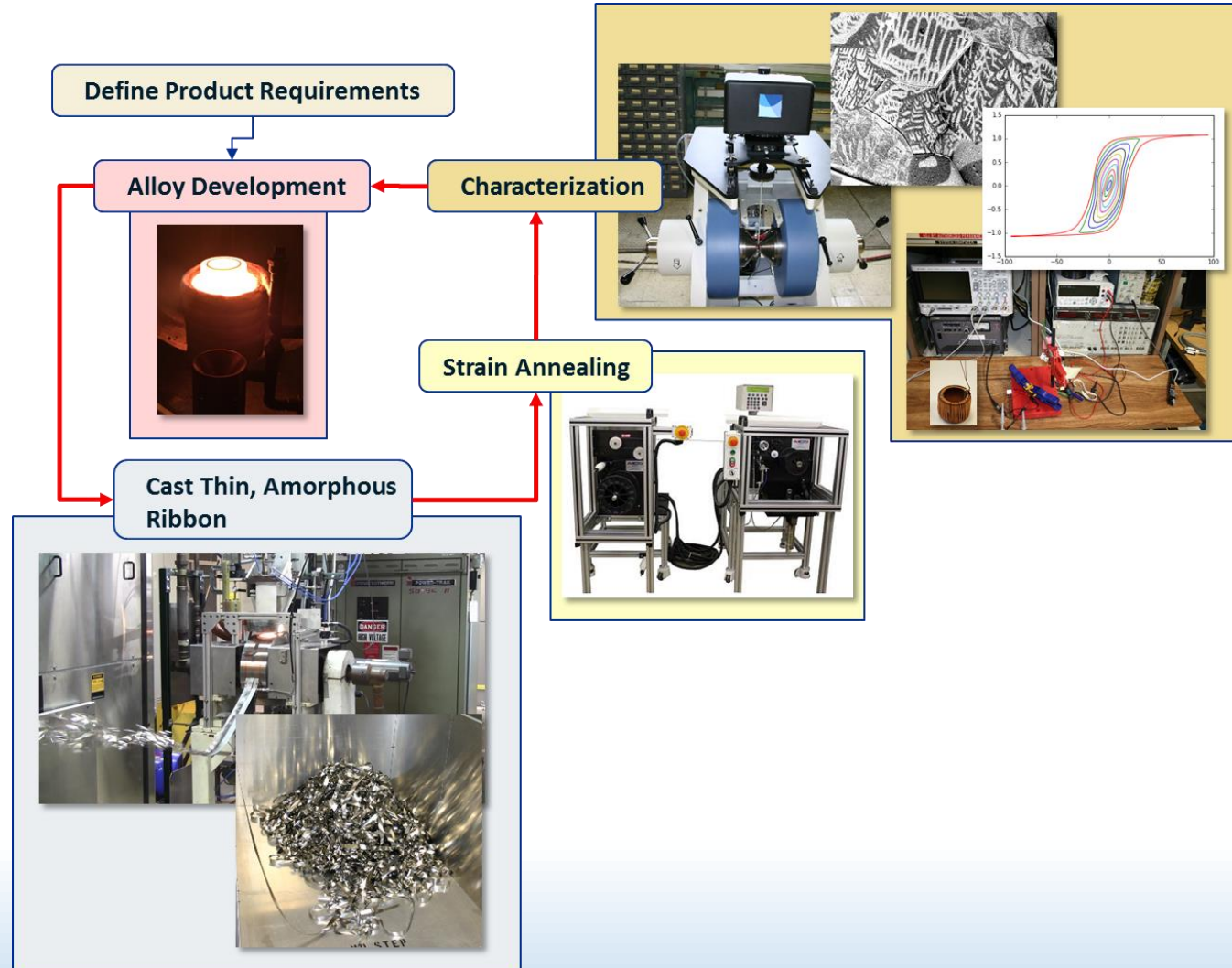
Very Pliable in As-Cast State



Wind these ribbons into the desired shapes for fabrication of components such as transformers, inductors, motor stators, etc.

# Enabling Materials for Electrified Propulsion

Establish capability for complete cycle of alloy development-to-component development for nanocrystalline soft magnetic materials

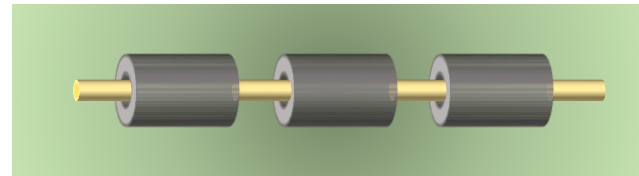


# Technologies Under Development for AATT Project

One milestone was to replace commercial inductor with a low-loss version capable of operating at 20 kHz for the AATT General Intelligent Motor Controller (GMIC).



GMIC specified commercial inductor is fairly bulky, is mounted on a dedicated circuit board, and requires a heat sink due to excess heat that is generated. Is the 2<sup>nd</sup> largest parasitic heat source in the system.



Nanocomposite bead inductor

Proposed “bead” inductor made from GRC-developed and fabricated material is conformable and produces 20 times less waste heat, **eliminating the need for a dedicated circuit board and significantly reducing the overall system cooling requirements**

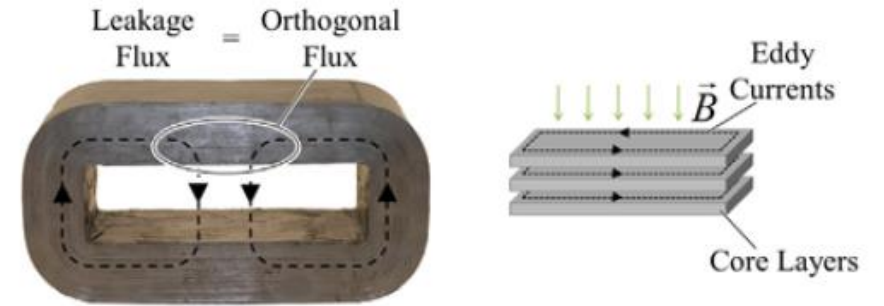


Inductor has been delivered to the controller team for testing on a testbed system.

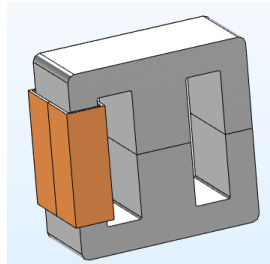


# In-House Magnetic Modeling

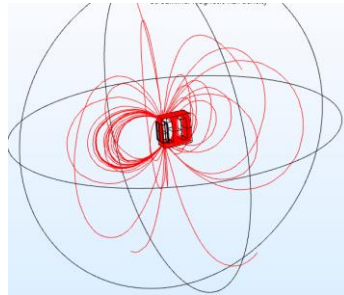
- As magnetic component geometries becomes more complex, predicting the system response based on the measured material properties will become crucial.
- COMSOL finite element modeling is being used to predict losses under relevant conditions.



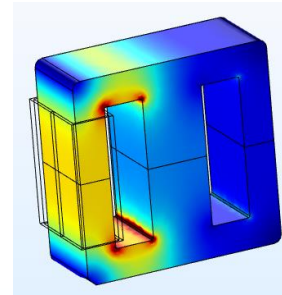
Actual core  
(without  
windings)



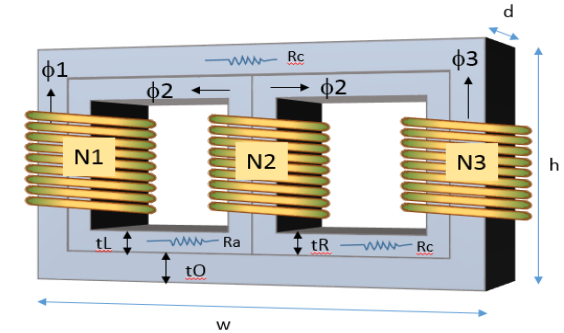
Modeled part with  
windings on one  
limb.



Representation of magnetic  
flux lines surrounding the  
part



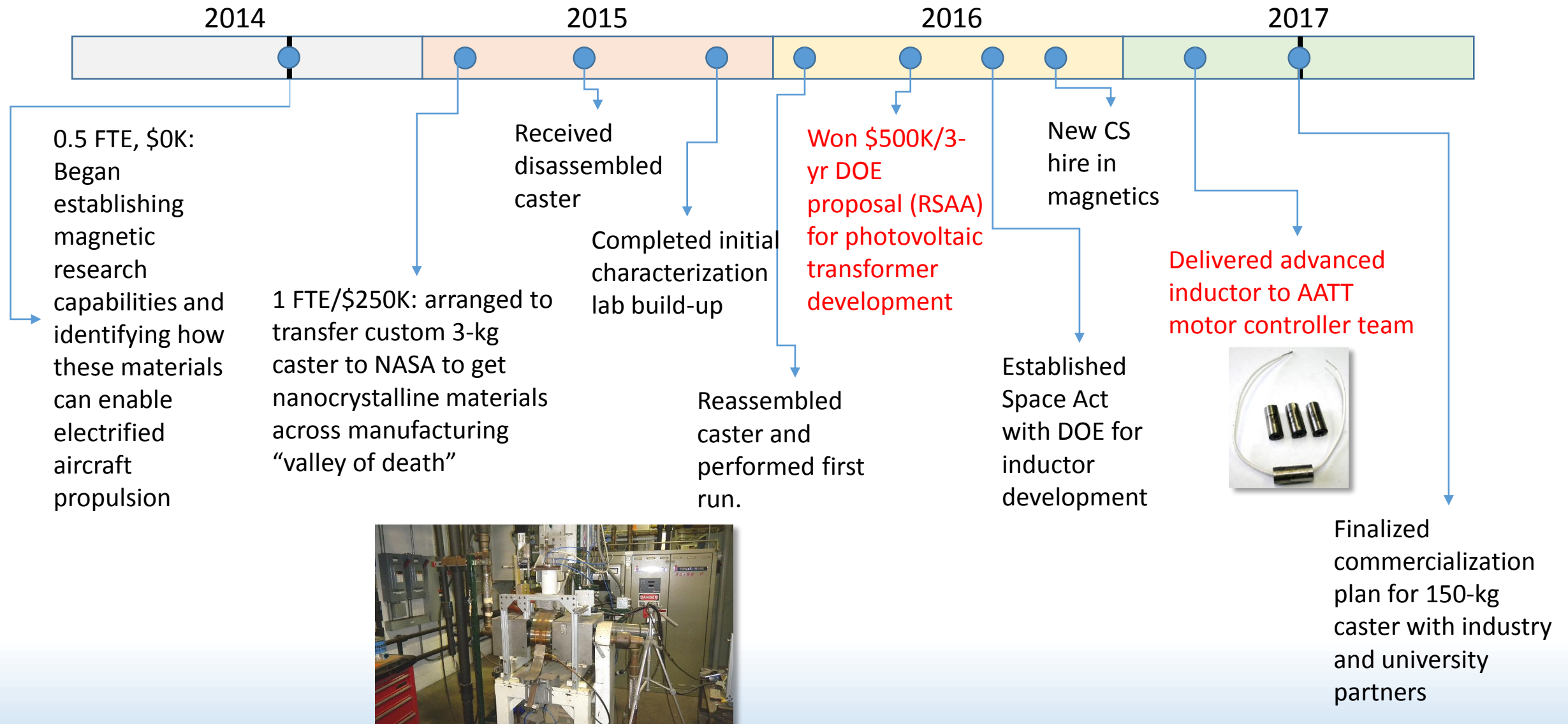
Magnetic flux density in  
the core



Model  
of a 3-  
phase  
inductor.



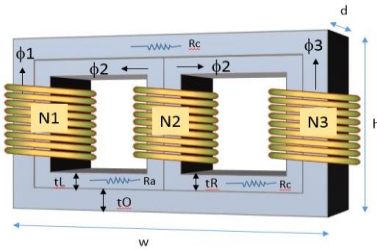
# Timeline of Magnetics Program





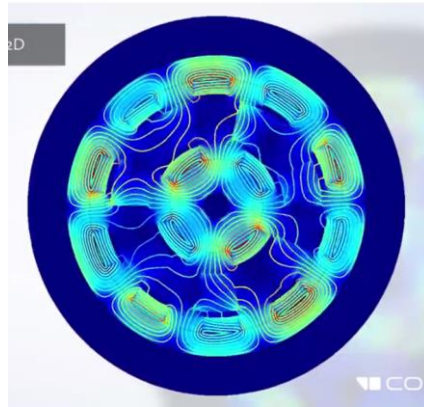
# Other High Impact Applications And Future Growth Areas

Other than the specific AATT inductor application, these materials can have a large impact in other power applications by reducing size and increasing efficiency.



Model of a 3-phase inductor.

Funded by DOE for photovoltaic-to-grid power conversion via advanced transformers.



Magnetic gears

Motor stators for vehicle electrification and generators.



Power Transformer Market ~\$10B

Electric Motor Market ~\$90B

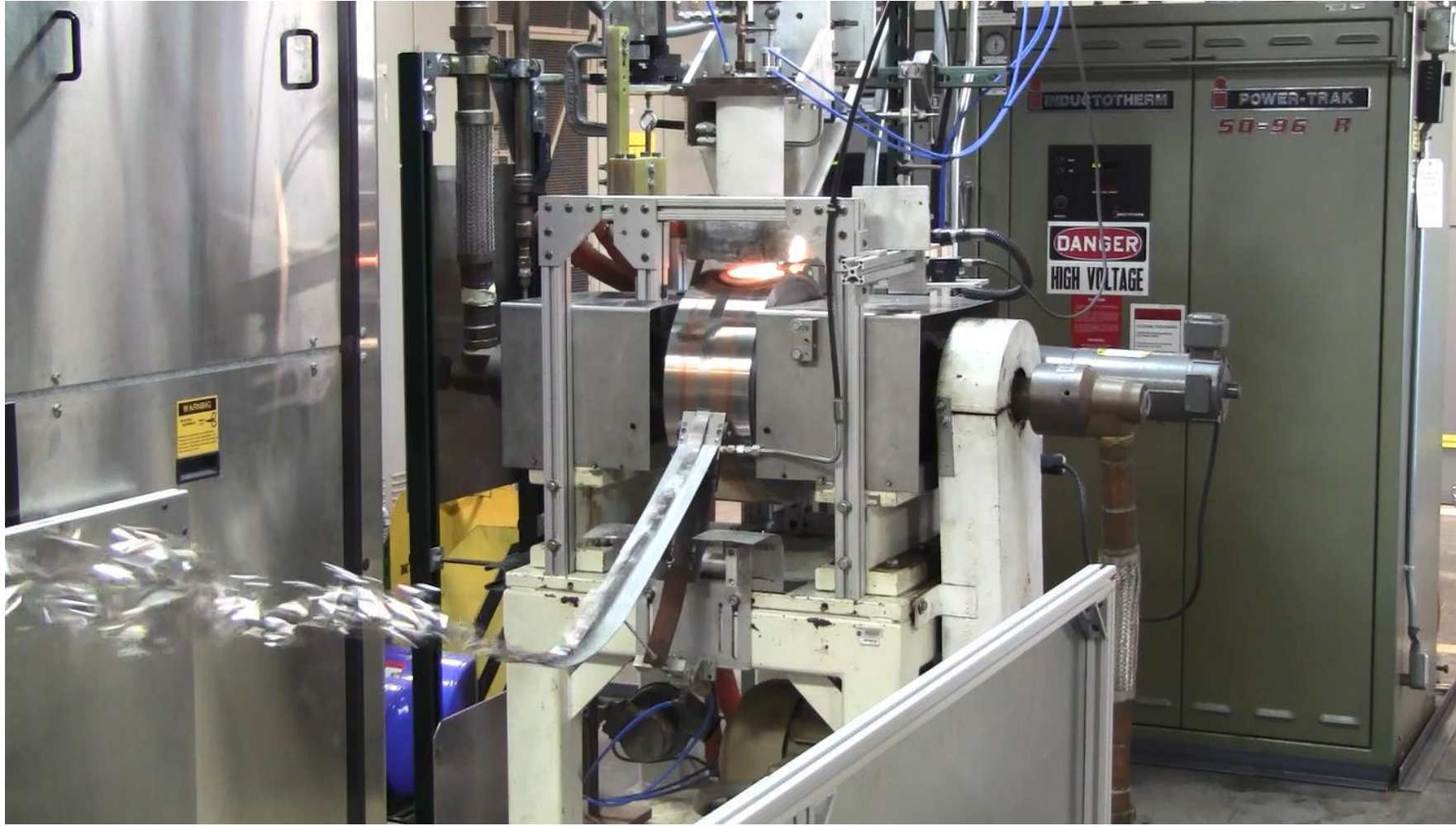
Power = Voltage • Current

or

Torque • Rotation speed

# Facilities

## Large (5-kg) Rapid Solidification Caster



# Facilities

## Small-Scale (50-g) Caster



- Produces 100 ft of 25-mm wide ribbon.
- Allows for fabrication of magnetic materials in inert environment.
- Rapid turn-around, several runs a day possible.



# Facilities

## Vibrating Sample Magnetometer



- 1) Variable temperature measurements from 4.2K to 1000°C.
- 2) Can measure both hard and soft magnetic materials..
- 3) VSM directly measures the intrinsic moment (or magnetization) of a sample from which one can calculate the magnetic induction  $B$ , ( $B = H + 4\pi M$ ).



## Permeameter

Fully characterizes soft magnetic components over a wide range of frequencies using toroidal or ribbon samples



## Core Testing System

Characterization of soft magnetic components under relevant conditions.



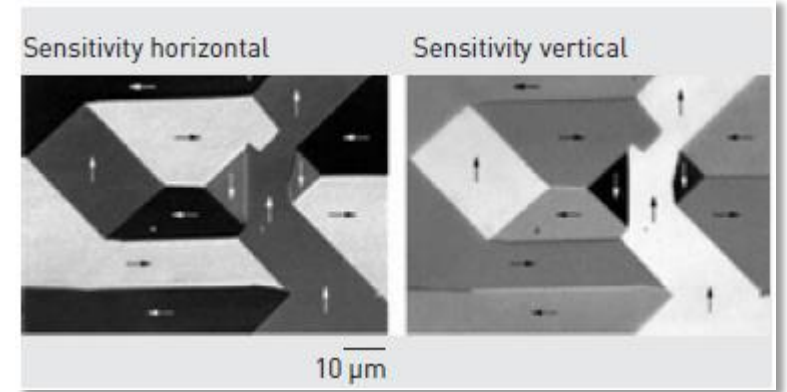
## Hysteresigraph

Characterization of Hard Magnetic materials

# Facilities



Directly images magnetic domains



- Kerr-Microscope & Magnetometer system is a facility for the visualization of magnetic domains.
- Direct observation of magnetic domain motion is key to understanding losses.
- High temperature measurements to 850 K (577 °C).
- Initial plans are to use this capability for alloy development and component-level measurements of transformer inductor cores (DOE SunLamp program)



## Diffractometer

Specially equipped for investigation of soft magnetic materials

PANalytical Empyrean



- System has easily reconfigurable source, optics, and stages.
- Currently capable of Cu, Co, and Mo sources.
- Ideal for phase analysis of nano-sized microstructural features in either reflective or transmission modes of crystalline or amorphous structures.
- 45-sample unattended operation
- High temperatures measurements up to 2300°C.
- Capable of performing investigations that previously required synchrotron beam time.